Winter emissions of carbon dioxide, methane and nitrous oxide from a minerotrophic fen under nature conservation management in north-east Germany

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SUMMARY

Drained peatlands are known to be important sources of carbon dioxide (CO_2) and nitrous oxide (N_2O). While CO_2 emissions occur mainly during the growing season, large N_2O emissions may occur during the non-growing season as well. Peatland re-wetting may be an effective measure to prevent those emissions. However, recent research shows that re-wetted peatlands may release large amounts of methane (CH_4) during the years immediately after re-wetting whereas abandonment of intensive grassland on drained peat soils possibly leads to low nutrient supply and thus to small greenhouse gas (GHG) emissions. Here we examine the role of extensification practices (such as abandonment of mineral fertilisation, reduced cutting frequency and a cattle-free winter period) on GHG emissions from a temperate peatland during winter. From November 2009 to March 2010 GHG measurements were made on a minerotrophic fen five years after intensive grassland use was abandoned. During the measurement period CO_2 and N_2O emissions amounted to 4.4 t ha^{-1} and 2.6 t ha^{-1} CO_2-equivalent, whilst CH_4 emissions were negligible. Altogether the site emitted 7 t ha^{-1} CO_2-equivalent, of which 37 % was N_2O, even though the winter 2009/2010 was extraordinarily cold. Thus, extensification of grassland use alone may not be sufficient to reduce GHG emissions from temperate peatlands.

KEY WORDS: peatland; greenhouse gas emissions; extensive grassland

INTRODUCTION

The greenhouse gases (GHG) carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O) contribute 63 %, 18 % and 6 % respectively to the global anthropogenic radiative forcing (Forster *et al*. 2007). In addition, N_2O plays an important role in the stratospheric ozone chemistry because it is an important source for nitric oxide (NO) and nitrogen dioxide (NO_2) in the upper atmosphere (Crutzen 1970). Owing to its relative stability it will remain the major ozone-depleting substance throughout the 21st century (Ravishankara *et al*. 2009).

Peatlands are known to be an important element of the global GHG cycles (Frolking *et al.* 2006). Although covering only 3 % of the world's land-surface area (Lappalainen 1996), they store 20 % to 30 % of the soils' C and N reserves (Martikainen *et al*. 1993). Natural peatlands are regarded as long-term sinks of C, converting atmospheric CO_2 to growing peat whilst emitting significant amounts of CH_4. Their net climatic impact is estimated to be a slight warming (if the effects of CH_4 emissions exceed those of carbon sequestration) or a slight cooling (if sequestration exceeds CH_4 emission), and depend on the time since peatland formation (Frolking *et al*. 2006). In contrast, drained peatlands act as a source of carbon and nitrogen, emitting CO_2 and N_2O from decomposing peat. Their net climate impact is a strong warming, with CO_2 effluxes up to 50 t ha^{-1} a^{-1} and N_2O effluxes up to 60 kg ha^{-1} a^{-1} (Couwenberg *et al*. 2011). Therefore, recently, re-wetting has been used as a measure to restore the peatlands' function as a C and N sink, whilst also having high value in terms of nature conservation. However, associated studies indicate that flooding of eutrophic drained fens may cause strong CH_4 emission peaks, possibly counteracting the reduction of CO_2 and N_2O emissions (Höper *et al*. 2008, Wilson *et al*. 2009, Glatzel *et al*. 2011). It is suggested that these enhanced emissions may be caused by anaerobic consumption of organic litter formed by plants that died back after flooding rather than by anaerobic consumption of peat (Hahn-Schöfl *et al*. 2010).

Nevertheless, drained eutrophic fens under agricultural use have a great potential to emit large fluxes of GHGs. Their potential to emit N_2O is significantly greater than that of virgin fens or drained but nutrient-poor peatlands (Regina *et al*. 1996). N_2O emissions are usually driven by a combination of several factors. Background emissions are controlled by long-term site-specific conditions such as nutrient status (e.g. C/N quotient, Maljanen *et al*. 2009), hydrological characteristics (Freeman *et al*. 1993, Martikainen *et al*. 1993), vegetation type (Glatzel *et al*. 2008) and soil temperature (Röver *et al*. 1998). Event-based emission peaks are induced by short-term changes of site-specific conditions such as freeze-thaw cycles (Teepe *et al*. 2000), fertiliser application (Ruser *et al*. 2001) and heavy rain. Hence, the annual release of N_2O can be very erratic, with a very large temporal and spatial variability (Flessa *et al*. 1995).

Despite this strong variability, non-growing-season effluxes may contribute 40–80 % of the annual emission of nitrous oxide on boreal minerotrophic peatlands (e.g. Alm *et al*. 1999, Regina *et al*. 2004, Maljanen *et al*. 2009) and temperate mineral soils (e.g. Flessa *et al*. 1995, Röver *et al*. 1998, Teepe *et al*. 2000). In contrast, studies of winter nitrous oxide emissions from temperate peatlands are scarce. Those existing either find a winter contribution of about 50 % (Beek *et al*. 2010) or N_2O effluxes too close to the detection limit to be further analysed (Hendriks *et al*. 2007).

In contrast to nitrous oxide, there are many reports of winter carbon dioxide and methane emissions from temperate and boreal wetlands. These emissions are significantly smaller outside the growing season (Dise 1992, Melloh & Crill 1996, Alm *et al*. 1999, Panikov & Dedysh 2000, Hao *et al*. 2006, Hendriks *et al*. 2007, Beek *et al*. 2010), contributing 10–40 % (CO_2) or about 10 % (CH_4) depending on site-specific climatic conditions during the winter.

In Mecklenburg-Western-Pomerania (north-eastern Germany) an area of 245,152 ha is covered by peatlands (Zauft *et al*. 2010), which account for 10.6 % of the federal state's land surface. By the early 1990s, 99 % of these peatlands were drained for agricultural use (Gelbrecht *et al*. 2001). It is now an integral part of Mecklenburg-Western-Pomerania's environmental policy to protect and restore peatlands. An important goal is the reduction of GHG emission and the calculation of its monetary values (Federal Environment Agency 2007). Several peatlands in this region are now part of National Parks, Biosphere Reserves or Nature Protection Zones. Some have already been re-wetted; on others, intensive agriculture is abandoned but extensive agricultural land use is still common.

Drained eutrophic fens are a strong source for CO_2 and N_2O, but re-wetting them may cause large emissions of CH_4. Nature conservation management guidelines include the abandonment of mineral fertiliser, a reduced cutting frequency and a cattle-free winter period. Since increasing wetness in winter may alter the anoxic layer of the soil and since cool conditions reduce microbial metabolism, we expect small net release rates of CO_2 and CH_4. Although winter N_2O effluxes may be large on temperate mineral soils (e.g. Flessa *et al*. 1995, Röver *et al*. 1998, Teepe *et al*. 2000), we expect small N_2O effluxes because land use abandonment has been shown to reduce N_2O effluxes due to the lack of inorganic fertiliser (Hendriks *et al*. 2007).

In the work reported here we measured the effects of extensive agricultural use on GHG effluxes from a drained eutrophic fen.

METHODS

Site description

The study site (108 ha) is part of the Biosphere Reserve "Schaalsee", in a small river valley ("Neuenkirchener Niederung") near Lake Schaalsee, 60 km east of Hamburg (Mecklenburg-Western Pomerania, northern Germany; 53°36′ N, 10°59′ E, see Figure 1). The regional climate is temperate with a maritime influence. Climatic data were derived from a 1 × 1 km grid provided by the German Weather Service. The data were extrapolated using data from nearby stations and a digital elevation model, and have been shown to correlate well with measured values (Müller-Westermeier 1995). Mean annual air temperature is 9.0 °C. The long-term mean temperature in January is 0.2 °C, and the average snow cover period is 5.9 days. Annual precipitation is 711 mm with an annual climatic water balance of +134 mm (Hippke, pers. comm.).

The fen is part of a river valley mire system that originated from a glacigenic tunnel valley. As its hydrology is dominated by groundwater flow, it is a percolation mire (Joosten & Succow 2001). The Bek, a dredged and channelled river, flows through the mire system. The surrounding area of the study site is characterised by agricultural land use on stagnosols originating from glacial till. These soils are typically decalcified down to 30–50 cm (Dann & Ratzke 2004) with pH 4–6 (Reuter 1962).

The study site was moderately drained during the 19th century. During the second half of the 20th century much deeper ditches were made (1.5–2.2 m), profoundly altering the water balance of the system. These ditches guide the main part of the outflow around the fen through a major ditch (L157), that formerly ran into the Bek (Figure 1).

From the 1970s until 2004 the study site was intensively used as grassland. Since then, the area has been managed under nature conservation guidelines, including abandonment of mineral fertilisation, reduced cutting frequency and a cattle-free winter period. Typical plant species of intensively used temperate grasslands are still dominant (such as *Alopecurus pratensis* L. and *Poa*

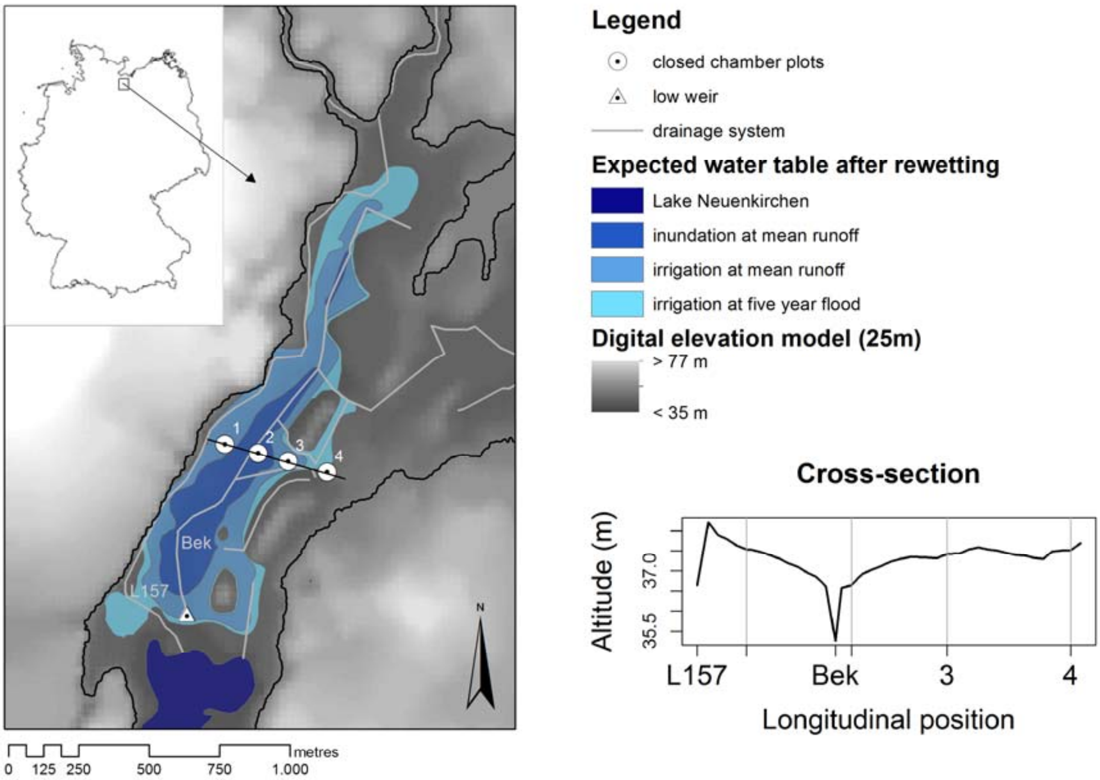

Figure 1. Map of the study site "Neuenkirchener Niederung" showing four measurement plots along the transect, the drainage system, expected water conditions after re-wetting, and landscape topography (digital elevation model with a raster resolution of 25 m). 'L157' identifies the main ditch. The inset shows the location in north-east Germany.

trivialis L.). Further species with large abundance or coverage are *Poa pratensis* L., *Taraxacum officinale* L., *Ranunculus repens* L. and *Holcus lanatus* L. indicating an ample nutrient supply from the soil (Ellenberg & Leuschner 2010). The plant community can be classified as *Molinio-Arrhenatheretea* Tx. 1937. The fen peat reaches more than 5 m deep, but the upper layer of peat (1 m) is strongly decomposed (H10–H8, von Post scale). At depths where decomposition is not too strong, peat originating from alder can be found at the western and at the eastern boundaries of the fen, whereas in the central parts the peat originates from reed and sedges (Table 1). Re-wetting of the mire system is planned but not yet implemented.

Study design

In October 2009, four GHG measurement plots were established along a transect crossing the "Neuenkirchener Niederung" from west to east. The plots were chosen to span the expected water conditions caused by the planned re-wetting of the mire (Figure 1). Plot 2 represents the wettest and Plot 4 the driest conditions, while Plots 1 and 3 will have intermediate water levels. In 2009, the area lying west of the Bek (Plot 1) was grazed by young male beef cattle. The area east of the Bek (Plots 2, 3, 4) was cut twice during the same year. We measured gas fluxes in removable chambers set on collars sunk permanently into the peat surface. We could not install these collars until the cattle had been removed from the plots, only three weeks before measurements began. The good fit of CO_2 effluxes *versus* soil temperature (see Figure 5) indicates, however, that any altered respiratory activity (due to root damage caused by installation of the collars) was negligible. Because of grazing, mowing and the protected status of the fen, no system of boardwalks could be laid; but the peat was dense and strongly humified, so ebullition events caused by physical disturbance when the chambers were approached were neither expected nor observed. The absence of stepwise linear increases in concentration, that would have been a sign of ebullition events (Chanton & Whiting 1995), supports this conclusion.

Each plot consisted of a triangle of collar locations (about 5 m apart). Since the nature of N_2O effluxes is erratic, an unfeasibly large number of collars would be needed to achieve statistically

Table 1. Characteristics of Plots 1 to 4: degree of decomposition (von Post scale); organic carbon (OC) proportion of dry mass [g/g] estimated from a 1m peat core; C/N quotient estimated from cores (n=5) of the uppermost 0.3 m.

Plot	1	2	3	4
identified macrofossils	alder	reed	reed/sedges	alder
degree of decomposition	H8–H10	H8–H10	H9–H10	H8–H10
OC	0.67	0.68	0.57	0.41
C/N	12.3	13.3	12.4	11.8

significant differences of N_2O effluxes between treatments (Folorunso & Rolston 1984). Thus, our approach was a compromise between covering spatial variability and being able to make all the necessary measurements during the short daylight hours in winter. The circular PVC collars (30 cm outside diameter, 20 cm tall, 8 mm thick) were inserted in slots cut in the peat with a knife (depth between 5 and 10 cm). GHG effluxes were estimated from concentration measurements using the non-steady-state chamber method (Livingston & Hutchinson 1995). Sampling was carried out every two weeks from November 2009 until March 2010, with additional sampling during freeze-thaw events. Overall, the measurement period lasted 129 days.

For each sampling, opaque PVC chambers (diameter 30 cm, height 30 cm) were carefully placed on top of the collars. The collar-chamber edge was sealed with a grooved ring from the inside and taped from the outside. Snow within the collar was not removed as snow removal is known to alter GHG effluxes (Maljanen *et al*. 2003, 2009). Four gas samples were taken (one every 15 minutes) with evacuated gas flasks (100 ml) that were attached to the chambers with a short (< 5 cm) silicone rubber tube. The samples were analysed by gas chromatography (Perkin Elmer Auto System) within a week for concentration of CO_2, N_2O and CH_4 using an Electron Capture Detector (ECD) and a Flame Ionization Detector (FID). The precision of analysis was about 10 vpb for methane, 70 vpb for nitrous oxide and 10 vpm for carbon dioxide.

Furthermore, we measured soil and air temperature, depth of water table, soil water, and nitrate concentration during each sampling period. High-resolution meteorological data (air temperature, precipitation, relative humidity, air pressure) covering the measurement period were collected by a weather station in Zarrentin, 7 km south-east of the study site. Peat characteristics and a height/depth profile along the transect were recorded once.

Data analysis

Gas efflux rates were estimated from the chamber concentration data using a prototype version of the R package “flux” (Jurasinski & Koebsch 2011). We used it to obtain the best linear fit to any three points out of the four possible groups of three (abc, abd, acd, bcd). The parameters of the model with the best linear fit (greatest R^2) were then used to obtain the change in concentration in the chamber headspace over the sampling time (dc/dt). When none of the models had $R^2 \geq 0.8$ the resulting efflux was discarded. The gas effluxes were calculated according to Fick’s first law and the assumption that diffusion is the single process of gas accumulation in the chamber headspace. Thus, the efflux rate f (mg m^{-2} h^{-1} for CO_2, µg m^{-2} h^{-1} for CH_4 and N_2O) was calculated from the molar mass M (g mol^{-1}) of the gas, the air pressure p (Pa), the chamber volume V (m^3), the gas constant R (m^3 Pa K^{-1} mol^{-1}), the chamber temperature T (K), the surface area A (m^2) and the concentration change over the sampling time dc/dt (vpm h^{-1} for CO_2, vpb h^{-1} for CH_4 and N_2O) as follows:

$$f = 10^3 \frac{MpV}{RTA} \cdot \frac{dc}{dt} \qquad [1]$$

Plot-wise efflux was calculated as the mean efflux of the three chambers. Estimation of total efflux rates during the sampling period was made by integrating the area under the efflux curves. To calculate the global warming potential (in CO_2-equivalents) we used the 100 year time horizon given by Forster *et al.* (2007) with 25 CO_2-eq for CH_4 and 298 CO_2-eq for N_2O.

Differences of efflux and of environmental variables among the four plots were tested for significance using the pair-wise Wilcoxon rank test with Bonferroni adjustment of P-values, because the data within single plots were not normally distributed in all cases. Generalised linear models were constructed to explain the variability within plots, and mixed effect models were built to explain the variability between plots. The best model was found by step-wise deletion of non-significant parameters (Crawley 2005). All statistical analyses were performed with R 2.12.0 (R Core Development Team 2011).

RESULTS

Winter 2009/2010 environmental characteristics

The winter of 2009/2010 was the harshest for 30 years in Mecklenburg-Western Pomerania. The monthly mean temperatures of December, January and February fell below the long-term mean temperatures (1970–2000) by 1.6, 4.4 and 1.4 °C, respectively. The lowest air temperature (−17 °C) was measured around 26th January. The long-term average snow-cover period of 6 days per winter was exceeded by more than 60 days (Figure 2). The snow cover reached a maximum thickness of about 40 cm after heavy snowfall at the end of January and lasted until the melting period one month later. During this period, the snow cover isolated the soil from fluctuating air temperature. Therefore, soil temperature remained constantly around 0 °C and the eastern area of the fen (Plots 2, 3, 4) continued to be unfrozen during the snow-cover period. In contrast, a strong freeze-thaw cycle occurred just when the mire became snow free again. At that time, the air temperature varied greatly between day and night ranging from +4 °C to -10 °C (Figure 2).

The water table depths during the measurement period differed slightly among the four plots according to the expected water table conditions after a possible re-wetting (Figure 1, Figure 4). The depth of water table at Plot 2 was significantly smaller than at Plot 4 (according to Wilcoxon rank test at $P < 0.05$). Water table depths at Plots 1 and 3 did not differ significantly from each other or from those at Plots 2 and 4 during the measurement period. Furthermore, parts of the study area (Plot 2, similar to “inundation at mean runoff”, Figure 1) were inundated by meltwater for two weeks from the beginning to the middle of March 2010. The soil temperature was similar in all four plots throughout the investigation period.

Gas effluxes

Greenhouse gas effluxes occurred during the whole measurement period even when the ground was snow-covered (Figure 3). The greatest effluxes of CO_2 and N_2O were recorded in November and March during periods with relatively high temperatures and without snow cover. At plot scale, GHG effluxes usually approximated a normal distribution except CO_2 effluxes at Plot 2 (Table 2).

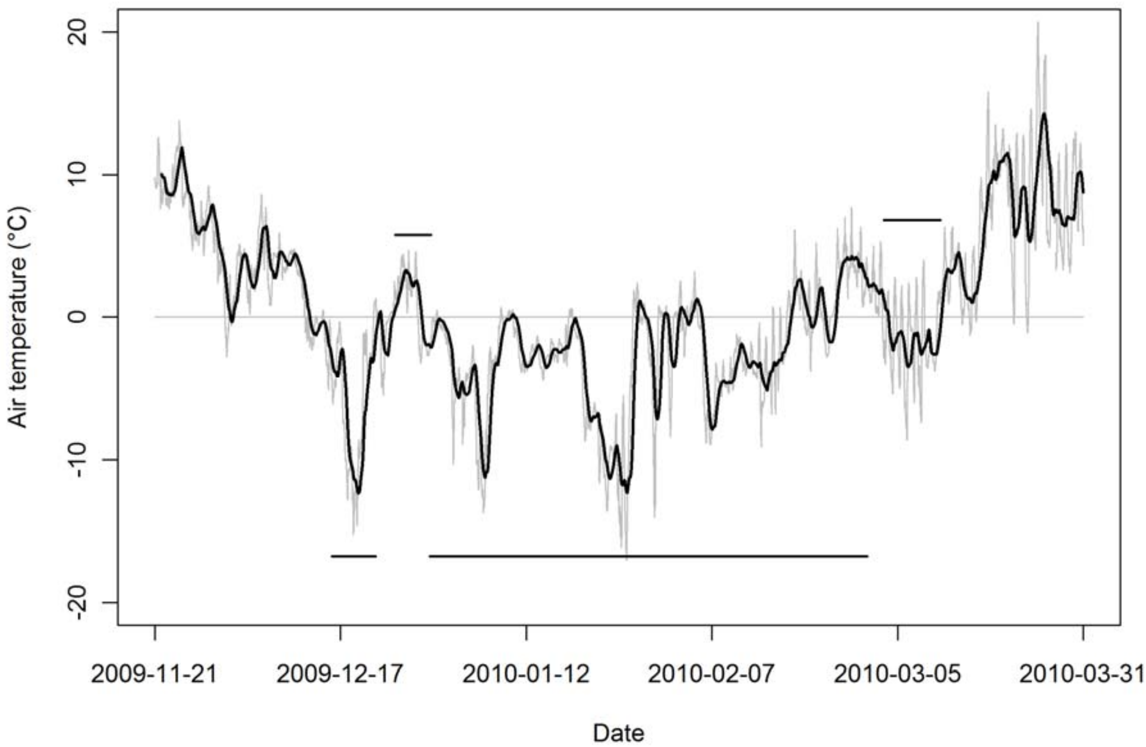

Figure 2. Air temperature at the weather station in Zarrentin, 7 km south-west of the study site during the winter 2009/2010 (thick line = daily running mean, thin line = 10-minute running mean). Upper horizontal bars (black) indicate thawing (December) and freeze-thaw cycles (March), lower horizontal bars (black) indicate snow-cover periods.

N_2O effluxes were similar at Plots 1, 2 and 3 (-380 to 420 µg m^{-2} h^{-1}) but significantly greater at Plot 4 (310 to 1900 µg m^{-2} h^{-1}) (Figure 4). On 10th March an N_2O efflux peak was observed at Plot 4 reaching 1400 µg m^{-2} h^{-1}. It followed a week-long freeze-thaw cycle that reached minimum temperatures of -10 °C at night and maximum temperatures of +4 °C during daytime.

CO_2 effluxes were similar at all four plots, ranging from a small uptake of -160 mg m^{-2} h^{-1} to 650 mg m^{-2} h^{-1}. CH_4 emissions were near zero throughout the measurement period except for

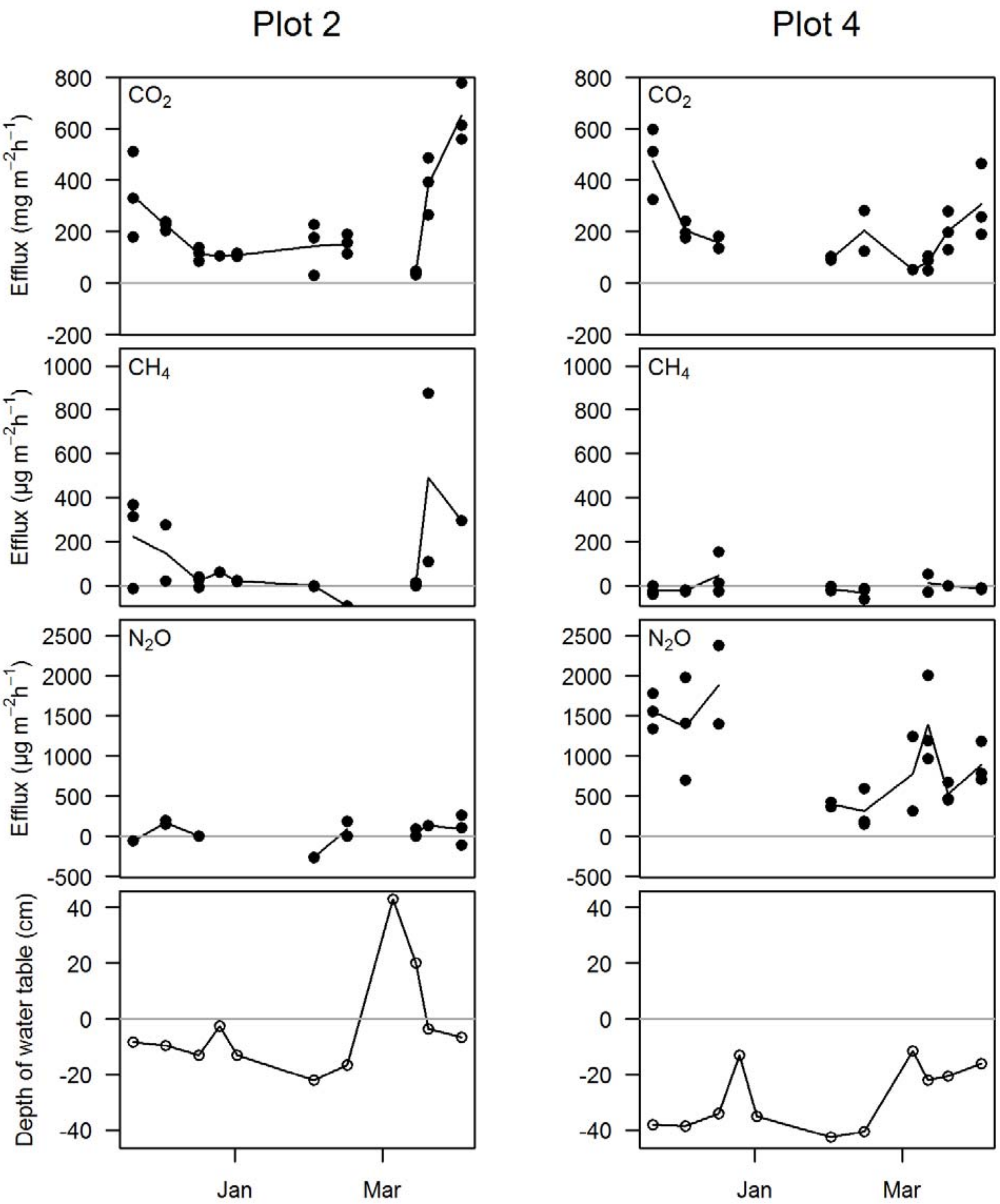

Figure 3. Gas effluxes and depth of water table (bottom row) at Plots 2 and 4 during the measurement period. These data span the hydrological range of the transect (Plots 1 and 3 have intermediate water level conditions, see Figure 4). For gas measurements, dots indicate single measurements and black lines indicate curves of mean effluxes. The zero line (grey) of the water table graphs marks the soil surface. Note the differences in scales.

Plot 2 at the end of November and for Plots 1 and 2 at the end of March after the snow-cover period. CH_4 effluxes ranged from -90 to 490 µg m^{-2} h^{-1} but did not differ significantly among plots (Figure 4).

CO_2, CH_4 and N_2O effluxes contributed 63 %, 0.2 % and 37 %, respectively, of the accumulated greenhouse gas emissions of the study site (Table 3). N_2O played the most important role

Table 2. Characteristics at four plots of gas effluxes during the 129-day measurement period November 2009 to March 2010). Mean and median effluxes and coefficients of variation (CV) are given. Non-normally distributed effluxes (according to Shapiro-Wilk test at P < 0.05) in *italics*.

	CO_2			CH_4			N_2O		
	Mean	Median	CV	Mean	Median	CV	Mean	Median	CV
Plot	(mg m^{-2} h^{-1})			(µg m^{-2} h^{-1})			(µg m^{-2} h^{-1})		
1	180	188	0.71	37	0	1.60	31	-28	3.92
2	*227*	*150*	*0.81*	118	42	1.49	24	47	5.45
3	132	124	0.99	11	11	1.37	26	10	9.58
4	198	203	0.66	-6	-14	-4.21	1013	896	0.55

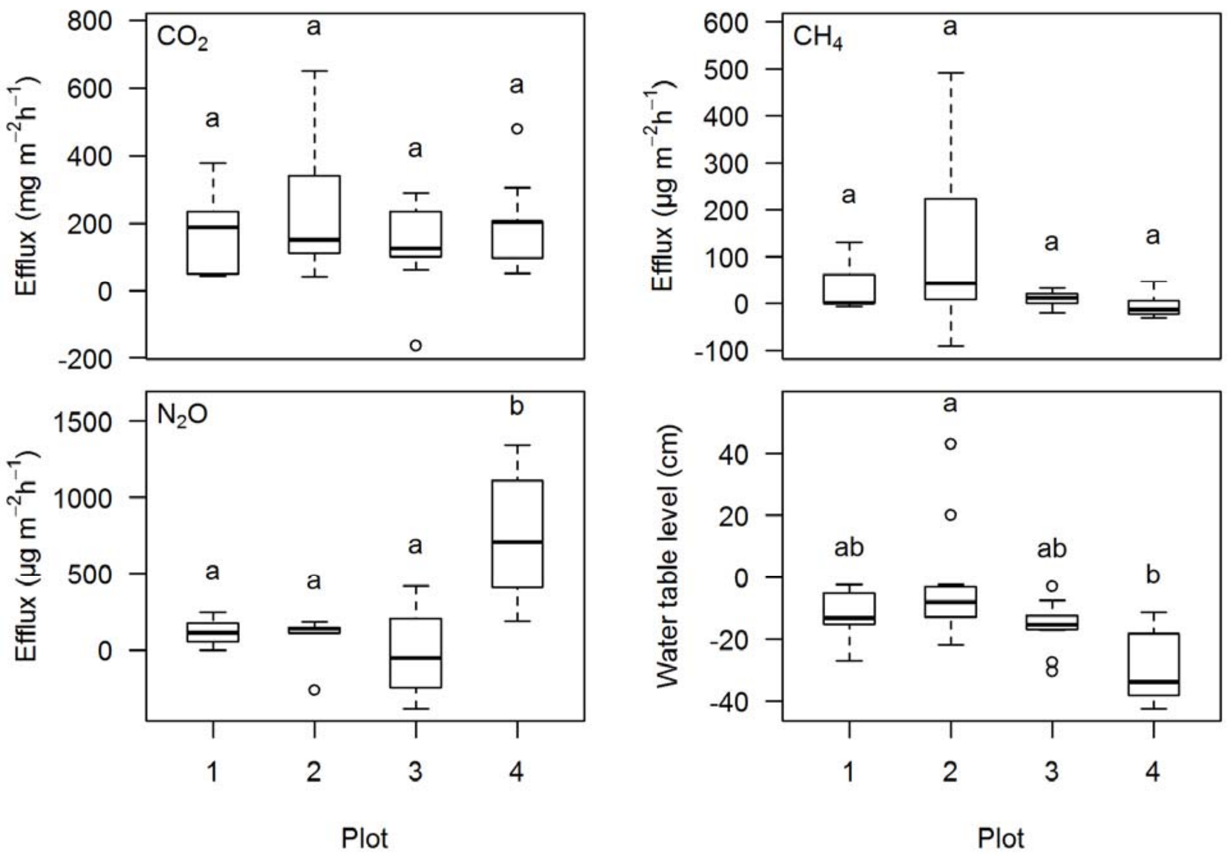

Figure 4. Plot-wise distribution of greenhouse gas effluxes and water table levels (relative to ground surface) during the measurement period. Thick line: median; box extent: interquartile range; whisker extent: marks the data lying within 1.5 times interquartlie range. Different lower case letters indicate significant differences between the plots at $P < 0.05$, according to pair-wise Wilcoxon-rank-test with Bonferroni P-value adjustment. Note the small number of samples (n < 12) for each plot.

Table 3: Total emissions from four plots of carbon dioxide, methane and nitrous oxide (t ha^{-1} CO_2-equivalents), contributions of CO_2, CH_4, N_2O (in %, *italics*) and mean depth of water table during the measurement period.

	all plots	Plot 1	Plot 2	Plot 3	Plot 4
CO_2	4.4	3.9	5.7	2.9	5.2
	63	*85*	*102*	*84*	*36*
CH_4	0.02	0.02	0.04	0.01	0.00
	0	*1*	*1*	*0*	*0*
N_2O	2.6	0.7	-0.2	0.6	9.2
	37	*14*	*-3*	*16*	*64*
Mean depth of water table (cm)	-15	-12	-3	-18	-28

(64 %) at Plot 4, whereas at Plot 2 N_2O was taken up during the measurement period. Plot 4 had the greatest release of GHG, emitting more than 14 t ha^{-1} CO_2-equivalents, whilst Plot 3 had the smallest (3.5 t ha^{-1}). On average, the study site emitted 7.0 t ha^{-1} CO_2-equivalents during the winter of 2009/2010.

Environmental controls

Carbon dioxide and methane effluxes did not differ among the plots (Figure 4). Therefore, generalised linear regression models were built by using environmental data covering the whole measurement period (Figure 5). Carbon dioxide efflux *Reco* (mg m^{-2} h^{-1}), in relation to soil temperature T_{soil}, can be described best (among the models tested) by:

$$Reco = R10^{\left(\frac{E0\cdot(T_{soil}-227.13)}{((283.15-227.13)\cdot(T_{soil}-227.13))-1}\right)} \quad [2]$$

($R^2 = 0.55$, $P < 0.001$), following the suggestion of Lloyd & Taylor (1994), with $R10$ = 429.7 mg m^{-2} h^{-1} being the reference efflux at 10 °C and $E0$ = 392.1 K.

Methane effluxes at the study site during the winter season can be best described by the following regression equation:

$$y = 288.6 - 91.3 \cdot \ln(bx) \quad [3]$$

($R^2 = 0.38$, $P < 0.001$) in which y is the CH_4 efflux (µg m^{-2} h^{-1}), x is the depth of water table (cm), and b = 1 cm^{-1}.

In contrast, nitrous oxide effluxes do differ between the plots (Figure 4). Therefore, the model was built using parameters that discriminate the plots in space. The best model found is:

$$z = 129.4 + 48.6 \cdot bx - 74.3 \cdot bx : w \quad [4]$$

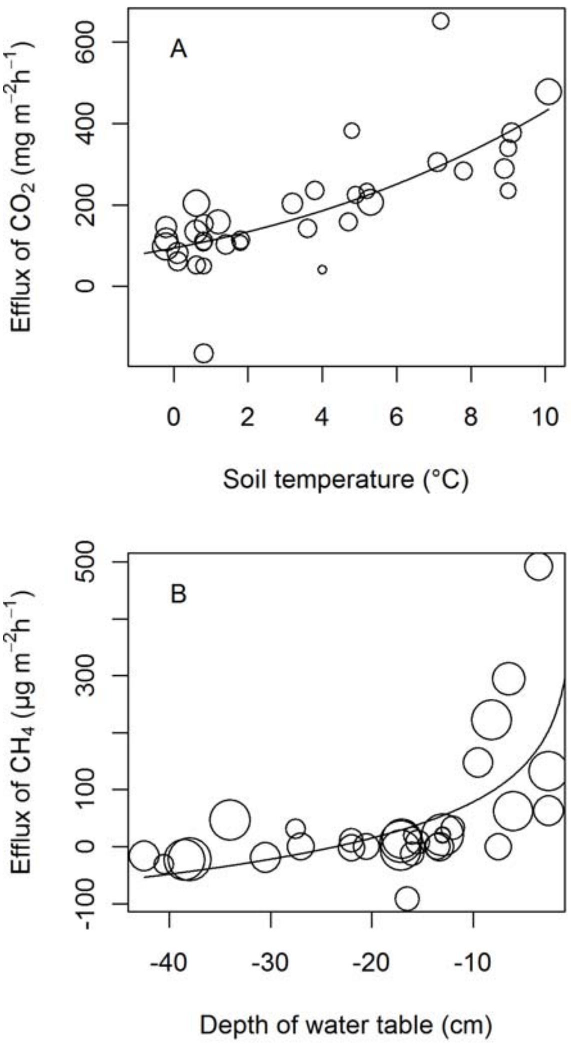

Figure 5. Relations of CO_2- (R^2=0.55, P < 0.001) and CH_4-fluxes (R^2=0.38, P < 0.001) to the relevant ecosystem controls. A circle represents the mean of plot-wise efflux measurements (n=3) with circle diameter being proportional to a third variable, namely depth of water table in (A) and air temperature in (B).

($P < 0.05$) in which z is the N_2O efflux (μg m^{-2} h^{-1}), x is the mean depth of water table (cm), w is organic carbon content (g g^{-1}), and $b = 1$ cm^{-1}, with $bx:w$ being the interaction between depth of water table by organic carbon content.

DISCUSSION

The radiative forcing of GHG emissions from the Neuenkirchener Niederung during the winter 2009/2010 was mainly caused by carbon dioxide (63 %) and nitrous oxide emissions (37 %). Methane emissions played only a minor role.

Compared with other studies, the global warming potential (GWP) of winter N_2O emissions (2.6 t ha^{-1} CO_2-equivalents) was similar to the GWP of annual N_2O emissions reported from a drained fen in Finland (2–4 t ha^{-1}, Nykänen *et al*. 1995) and to the GWP of winter N_2O production of organic grassland soils in the Netherlands (~2.8 t ha^{-1} a^{-1}, derived from Beek *et al*. 2010). Given the extraordinarily cold winter of 2009/2010 with its long period of snow cover, and that the greatest nitrous oxide emissions occurred in late autumn (November) and early spring (March), our results resemble an emission pattern typical for a boreal climate as described by Alm *et al*. (1999) rather than an emission pattern for a temperate climate where the largest N_2O emissions may occur during the winter months of December to February (Flessa *et al* 1995, Teepe *et al*. 2000). For this reason, the N_2O emissions measured in this study seem likely to have been smaller than during a climatically normal winter.

The snow cover during the winter of 2009/2010 prevented the soil from becoming deeply frozen. In such cases, nitrous oxide effluxes during freeze-and-thaw events are typically smaller than effluxes from formerly deeply frozen soils (Maljanen *et al*. 2009). In contrast, effluxes during the snow-cover period are typically greater if the soil is not deeply frozen. For this reason, the distribution of N_2O effluxes in this study may not be as skewed as reported by others (Flessa *et al.* 1995). Hence, the timing of snow cover development and frost during the beginning of winter is an important factor that controls N_2O emissions in the non-growing season (Maljanen *et al.* 2003). Nevertheless, an N_2O efflux peak of 1,400 μg m^{-2} h^{-1} at Plot 4 was detected after one week of intensive freezing and thawing of snow-free soil. Pihlatie *et al*. (2010) reported a time span of one week after freezing and thawing to be the period of greatest N_2O release during such a freeze-thaw cycle.

Although the land use of the study site was extensified five years before the measurements were carried out and despite the extraordinarily cold winter, the N_2O emissions of the Neuenkirchener Niederung are still as large as reported for intensively used grassland on organic soils (Velthof & Oenema 1995, Augustin *et al*. 1998). Some authors show that fertilisation is not necessarily needed on peatlands to produce N_2O effluxes as much as 10,000 μg m^{-2} h^{-1} (Maljanen *et al*. 2009) or 56.4 kg ha^{-1} a^{-1} N_2O-N (Flessa *et al.* 1998). Depth of water table and organic carbon content may be much more important drivers of N_2O emissions in our case (Equation 4). These were shown to be important controls in several other studies (e.g. Freeman *et al*. 1993, Martikainen *et al*. 1993, Maljanen *et al*. 2009).

CO_2 efflux can be modelled with our data following Lloyd & Taylor (1994) and is thus driven by soil temperature. Although soil temperature varied only within an interval of 10 °C during the measurement period, a clear dependence of CO_2 efflux on soil temperature was observed (Equation 2). Since grassland use has been constant for decades and the study site is either used for hay production or cattle grazing, C uptake of the soil during the growing season is improbable. Therefore, the CO_2 balance of the system can be described by CO_2 emissions alone showing that the study site acts as a source for CO_2. The winter CO_2 emissions from the study site amount to 4.4 t ha^{-1}, which is closer to the winter CO_2 emissions of a boreal minerotrophic fen (2.5 t ha^{-1}, derived from Alm *et al*. 1999) than to the winter CO_2 emissions of an abandoned maritime peat meadow (11.0 t ha^{-1}, derived from Hendriks *et al*. 2007), again indicating the impact of the extraordinarily cold winter 2009/2010. In contrast, the CO_2 balance from virgin fens is generally close to zero or even negative (Frolking *et al*. 2006) as their hydrology inhibits oxic decomposition, and carbon is sequestered.

Winter methane effluxes were close to the detection limit and contributed less than 0.2 % (0.02 t ha^{-1} CO_2-equivalents) to the total winter emissions of the study site. Annual methane effluxes from similar fen sites in Finland (~0.04 t ha^{-1}, derived from Nykänen *et al*. 1995) are in the same order of magnitude. In contrast, annual methane emissions from virgin fen sites are two orders of magnitude greater (8–15 t ha^{-1} CO_2-equivalents, derived from Dise 1992, Nykänen *et al*. 1995, Melloh & Crill 1996), but N_2O emissions from such virgin sites are typically close to the detection limit.

To get an idea about the magnitude of the emission potential from the study site we assumed that winter carbon dioxide emissions contribute 25 % (23 % according to Alm *et al.* 1999, 34 %, derived from Hendriks *et al.* 2007), winter methane emissions contribute 10 % (Dise 1992, Alm *et al.* 1999) and winter nitrous oxide emissions contribute

50 % (40–80 % according to Alm *et al*. 1999, Maljanen *et al*. 2009, Beek *et al.* 2010) of the annual emissions. Therefore, the annual GHG emissions of the study site are estimated at 18 (CO_2), 0.2 (CH_4) and 5 (N_2O) t ha^{-1} CO_2-equivalents, which would total about 23 t ha^{-1}, with the winter contributing 30 %. For this reason, our assumption of small net GHG emissions during winter must be rejected. This indicates that winter GHG emissions from temperate peatlands should be taken into account when comparing the GHG emission potentials of extensively used and re-wetted mires.

In addition, both young male beef cattle and dairy cattle emit methane. Given that one lactating cow (weight 650 kg, milk yield 6500 kg a^{-1}, CH_4 emission 135 kg a^{-1}, Jentsch *et al*. 2009) needs about 0.8 ha of extensively used grassland, the net annual methane emissions of the study site would increase to about 4 t ha^{-1} CO_2-equivalents, and the annual GHG emissions to 27 t ha^{-1}. Therefore, extensification of land use without re-wetting might not reduce the GHG emissions of the Neuenkirchener Niederung. According to our findings, aiming to reduce the GWP of peatlands is not a suitable objective. Only a permanent and effective rise of the water table to a level close to the ground surface will lead to permanently reduced CO_2 and N_2O emissions.

However, re-wetting of drained fens may cause raised CH_4 emissions that possibly counteract the reduced CO_2 and N_2O emissions (Höper *et al*. 2008, Wilson *et al.* 2009, Glatzel *et al*. 2011). Field studies of GHGs from these dynamic and young ecosystems are few, and seldom cover long time spans. On the one hand, increased methane emissions after re-wetting might originate from dead inundated grassland plants such as *Phalaris arundinacea* L. (Hahn-Schöfl *et al*. 2010). On the other hand, typical wetland plants such as *Typha* spp. or *Phragmites australis* L. are absent directly after re-wetting, but they are known to be important vectors for CH_4 emissions in virgin peatlands (Chanton *et al*. 1993, Van der Nat *et al*. 1998). Thus, it can be assumed that these large CH_4 emissions prevail after re-wetting as long as the plant composition of the ecosystem is shifting towards a new equilibrium state reflecting altered hydrological conditions of the habitat. On a raised bog in north-east Germany, Bönsel & Sonneck (2011) showed that this shift in plant composition after re-wetting takes at least a decade. Therefore, we propose that future research on GHG emissions from peatlands should focus:

1) on study sites at different stages of re-wetting, in order to develop a time series model of CH_4 emission dynamics after re-wetting; and
2) on the estimation of CH_4 emission potentials of different vegetation types from drained peatlands, in order to better predict the possible CH_4 output of inundated grassland plant communities.

When these points are addressed, comparisons of GWPs of drained and re-wetted peatlands should be more accurate and reliable than comparisons of annual GHG budgets derived from single- or two-year measurement campaigns.

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REFERENCES

Alm, J., Saarnio, S., Nykänen, H., Silvola, J. & Martikainen, P.J. (1999) Winter CO_2, CH_4 and N_2O fluxes on some natural and drained boreal peatlands. *Biogeochemistry*, 44, 164–186.

Augustin, J., Merbach, W. & Rogasik, J. (1998) Factors influencing nitrous oxide and methane emissions from minerotrophic fens in northeast Germany. *Biology and Fertility of Soils*, 28, 1–4.

Beek, C.L., Pleijter, M., Jacobs, C.M.J., Velthof, G. L., Groeningen, J.W. & Kuikman, P.J. (2010) Emissions of N_2O from fertilized and grazed grassland on organic soil in relation to groundwater level. *Nutrient Cycling in Agroecosystems*, 86, 3, 331–340.

Bönsel, A. & Sonneck, A-G. (2011) Effects of a hydrological protection zone on the restoration of a raised bog: a case study from Northeast-Germany 1997–2008. *Wetlands Ecology & Management*, 19, 183–194.

Chanton, J.P., Whiting, G.J., Happel, J.D. & Gerard, D. (1993) Contrasting rates and diurnal patterns of methane emission from emergent aquatic macrophytes. *Aquatic Botany*, 46, 111–128.

Chanton, J.P. & Whiting, G.J. (1995) Trace gas exchange in freshwater and coastal marine environments: ebullition and transport by plants. In: Matson, P.A. & Harriss, R.C. (eds.) *Biogenic Trace Gases: Measuring Emissions From Soil and Water*, Blackwell Science Ltd., UK, Chapter 4, 98–125.

Couwenberg, J., Thiele, A., Tanneberger, F., Augustin, J., Bärisch, S. & Dubovik, D. (2011) Assessing greenhouse gas emissions from peatlands using vegetation as a proxy. *Hydrobiologia*, 674, 1, 67–89.

Crawley, M.J. (2005) *Statistics – An Introduction Using R*. Wiley, Chichester, 214–216.

Crutzen, P.J. (1970) The influence of nitrogen oxides on the atmospheric ozone content. *Quarterly Journal of the Royal Meteorological Society*, 96, 320–325.

Dann, T. & Ratzke, U. (2004) Böden (Soils). In: Katzung, G. (ed.) *Geologie von Mecklenburg-Vorpommern (Geology of Mecklenburg Western-Pomerania)*, E. Schweizerbart, Stuttgart, Chapter 6.12, 489–508 (in German).

Dise, N.B. (1992) Winter fluxes of methane from Minnesota peatlands. *Biogeochemistry* 17, 71–83.

Ellenberg, H. & Leuschner, C. (2010) Zeigerwerte der Pflanzen Mitteleuropas (Indication values of plants of central Europe). In: Ellenberg, H. & Leuschner, C. (eds.) *Vegetation Mitteleuropas mit den Alpen (The Vegetation of Central Europe with the Alps)*, Chapter 27, 109 pages. Available online at http://www.utb-mehr-wissen.de.

Federal Environment Agency (Umweltbundesamt) (2007) Regional climate changes: Recent findings – WETTREG: A statistical regionalization model, 27 pages. Online at http://www.umweltdaten.de/publikationen/fpdf-l/3543.pdf.

Flessa, H., Dörsch, P. & Beese, F. (1995) Seasonal variation of N_2O and CH_4 fluxes in differently managed arable soils in southern Germany. *Journal of Geophysical Research*, 100, D11, 23115–23124.

Flessa, H., Wild, U., Klemisch, M. & Pfadenhauer, J. (1998) Nitrous oxide and methane fluxes from organic soils under agriculture. *European Journal of Soil Science*, 49, 327–335.

Folorunso, O.A. & Rolston, D.E. (1984) Spatial variability of field-measured denitrification gas fluxes. *Soil Science Society of America Journal*, 48(6), 1214–1219.

Forster, P., Ramaswamy, V., Artaxo, P., Berntsen, T., Betts, R., Fahey, D.H., Haywood, J., Lean, J., Lowe, D.C., Myhre, G., Nganga, J., Prinn, R., Raga, G., Schulz, M. & Van Dorland, R. (2007) Changes in atmospheric constituents and in radiative forcing. In: Solomon, S., Qin, D., Manning, M., Chen, Z., Marquis, M., Averyt, K.B., Tignor, M. & Miller, H.L. (eds.) *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, Chapter 2, 130–234.

Freeman, C., Lock, M.A. & Reynoldy, B. (1993) Fluxes of CO_2, CH_4 and N_2O from a Welsh peatland following simulation of water table draw-down: Potential feedback to climatic change. *Biogeochemistry*, 19, 51–60.

Frolking, S., Roulet, N. & Fuglestvedt, J. (2006) How northern peatlands influence the Earth's radiative budget: Sustained methane emission versus sustained carbon sequestration. *Journal of Geophysical Research*, 111, G01008.

Gelbrecht, J., Koppisch, D. & Lengsfeld, H. (2001) Nordostdeutsche Niedermoore als Akkumulationsräume (The fens of north-east Germany as an accumulation area). In: Succow, M. & Joosten, H. (eds.) *Landschaftsökologische Moorkunde*, E. Schweizerbart, Stuttgart, 38–40 (in German).

Glatzel, S., Forbrich, I., Krüger, C., Lemke, S. & Gerold, G. (2008) Small scale controls of greenhouse gas release under elevated N deposition rates in a restoring peat bog in NW Germany. In: *Biogeosciences*, 5, 925–935.

Glatzel, S., Koebsch, F., Beetz, S., Hahn, J., Richter, P. & Jurasinski, G. (2011) Maßnahmen zur Minderung der Treibhausgasfreisetzung aus Mooren im Mittleren Mecklenburg (Measures to reduce greenhouse gas emissions from peatlands in Mid-Mecklenburg, Germany). *Telma*, Beiheft 4, 85–105 (in German).

Hahn-Schöfl, M., Zak, D., Minke, M., Gelbrecht, J., Augustin, J. & Freibauer, A. (2010) Organic sediment formed during inundation of a degraded fen grassland emits large fluxes of CH_4 and CO_2. *Biogeosciences,* 8, 1539–1550.

Hao, Q.-J., Wang, Y.-S., Song, C.-C. & Huang Y. (2006) Contribution of winter fluxes to the annual CH_4, CO_2 and N_2O emissions from freshwater marshes in the Sanjiang Plain. *Journal of Environmental Sciences*, 18(2), 270–275.

Hendriks, D.M.D., van Huissteden, J., Dolman, A.J. & van der Molen, M.K. (2007) The full greenhouse gas balance of an abandoned peat meadow. *Biogeosciences*, 4, 411–424.

Hippke, M. (personal communication) Water balance of the Neuenkirchener Niederung. Biosphere Reserve Schaalsee.

Höper, H., Augustin, J., Cagampan, J.P., Drösler, M., Lundin, L., Moors, E., Vasander, H., Waddington, J.M. & Wilson, D. (2008) Restoration of peatlands and greenhouse gas balances. In: Strack, M. (ed.) *Peatlands and Climate Change*, International Peat Society, Saarijärvi, 184–212.

Jentsch, W., Piatkowski, B., Schweigel, M. & Derno, M. (2009) Quantitative results for methane production of cattle in Germany. *Archiv*

Tierzucht, 52(6), 587–592.

Joosten, H. & Succow, M. (2001) Hydrogenetische Moortypen (Hydrogenetic Mire Types). In: Succow, M. & Joosten, H. (eds.) *Landschafts-ökologische Moorkunde*, E. Schweizerbart, Stuttgart, 234–240 (in German).

Jurasinski, G. & Koebsch, F. (2011) Flux: flux rate calculation from dynamic closed chamber measurements. R package version 0.1-4, Rostock. Available online at http://cran.r-project.org/ web/packages/flux.

Lappalainen, E. (ed.) (1996) *Global Peat Resources*. International Peat Society, Jyväskylä, 368 pages.

Livingston, G.P. & Hutchinson, G.L. (1995) Enclosure-based measurement of trace gas exchange: applications and sources of error. In: Matson, P.A. & Harriss, R.C. (eds.) *Biogenic Trace Gases – Measuring Emissions from Soil and Water*, Blackwell Science Ltd., UK, Chapter 2, 14–51.

Lloyd, J. & Taylor, J.A. (1994) On the temperature dependence of soil respiration. *Functional Ecology*, 8(3), 315–323.

Maljanen, M., Liikanen, A., Silvola, J. & Martikainen, P.J. (2003) Nitrous oxide emissions from boreal organic soil under different land-use. *Soil Biology & Biochemistry*, 35, 689–700.

Maljanen, M., Virkajärvi, P., Hytönen, J., Öquist, M., Sparrman, T. & Martikainen, P.J. (2009) Nitrous oxide production in boreal soils with variable organic matter content at low temperature - snow manipulation experiment. *Biogeosciences*, 6, 2461–2473.

Martikainen, P.J., Nykänen, H., Crill, P. & Silvola, J. (1993) Effect of a lowered water table on nitrous oxide fluxes from northern peatlands. *Nature*, 366, 51–53.

Melloh, R.A. & Crill, P.M. (1996) Winter methane dynamics in a temperate peatland. *Global Biogeochemical Cycles*, 10(2), 247–254.

Müller-Westermeier (1995) Numerisches Verfahren zur Erstellung klimatologischer Karten (A numeric method creating climatologic maps). *Berichte des Deutschen Wetterdienstes (Reports of the German Weather Service)*, 193, 1–17.

Nykänen, H., Alm, J., Lang, K., Silvola, J. & Martikainen, P.J. (1995) Emissions of CH_4, N_2O and CO_2 from a virgin fen and a fen drained for grassland in Finland. *Journal of Biogeography*, 22, 351–357.

Panikov, N.S. & Dedysh, S.N. (2000) Cold season CH_4 and CO_2 emission from boreal peat bogs (West Siberia): Winter fluxes and thaw activation dynamics. *Global Biogeochemical Cycles* 14(4), 1071–1080.

Pihlatie, M.K., Kiese, R., Brüggemann, N., Butterbach-Bahl, K., Kieloaho, A-J., Laurila, T., Lohila, A., Mammarella, I., Minkkinen, K., Penttilä, T., Schönborn, J. & Vesala, T. (2010) Greenhouse gas fluxes in a drained peatland forest during spring frost-thaw event. *Biogeosciences*, 7, 1715–1727.

R Core Development Team (2011) *R: A Language and Environment for Statistical Computing*. R Foundation for Statistical Computing, Vienna. Available online at http://www.R-project.org/.

Ravishankara, A.R., Daniel, S.J. & Portmann, R.W. (2009) Nitrous oxide (N_2O): the dominant ozone-depleting substance emitted in the 21st century. *Science*, 326, 123–125.

Regina, K., Nykänen, H., Silvola, J. & Martikainen, P.J. (1996) Fluxes of nitrous oxide from boreal peatlands as affected by peatland type, water table and nitrification capacity. *Biogeochemistry*, 35, 401–418.

Regina, K., Syväsalo, E., Hannukkala A. & Esala, M. (2004) Fluxes of N_2O from farmed peat soils in Finland. *European Journal of Soil Science*, 55, 591–599.

Reuter, G. (1962) Tendenzen d. Bodenentwicklung im Küstenbezirk Mecklenburgs (Tendencies of soil development in the coastal district of Mecklenburg). *Wissenschaftliche Abhandlungen Nr. 49*, Deutsche Akademie d Landwirtschafts-wissenschaften zu Berlin (in German).

Röver, M., Heinemeyer, O. & Kaiser, E-A. (1998) Microbial induced nitrous oxide emissions from an arable soil during winter. *Soil Biology & Biochemistry*, 30(14), 1859–1865.

Ruser, R., Flessa, H., Schilling, R., Beese, F. & Munch, J.C. (2001) Effect of crop-specific field management and N fertilization on N_2O emissions from a fine-loamy soil. *Nutrient Cycling in Agroecosystems*, 59, 177–191.

Teepe, R., Brumme, R. & Beese, F. (2000) Nitrous oxide emissions from frozen soils under agricultural, fallow and forest land. *Soil Biology & Biochemistry*, 32, 1807–1810.

Van der Nat, F-J.W.A., Middelburg, J.J., van Meteren, D. & Wielemakers, A. (1998) Diel methane emission patterns from *Scirpus lacustris* and *Phragmites australis*. *Biogeochemistry*, 41, 1–22.

Velthof, G.L. & Oenema, O. (1995) Nitrous oxide fluxes from grassland in the Netherlands: II. Effects of soil type, nitrogen fertilizer application and grazing. *European Journal of Soil Science*, 46, 541–549.

Wilson, D., Alm, J., Laine, J., Byrne, K.A., Farrell, E.P. & Tuittila, E-S. (2009) Rewetting of cutaway peatlands: are we re-creating hot spots of methane emissions? *Restoration Ecology*, 17(6), 796–806.

Zauft, M., Fell, H., Glaßer, F., Rosskopf, N. &

Zeitz, J. (2010) Carbon storage in the peatlands of Mecklenburg-Western Pomerania, north-east Germany. *Mires and Peat*, 6(04), 1–12.

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